SIMULATIONS OF THE EFFECTS OF ION SPACE-CHARGE ON VACUUM POWER FLOW IN INDUCTIVE ENERGY STORE PULSED POWER SYSTEMS

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In this paper we present results from recent particle-in-cell (PIC) simulations regarding power-flow between a plasma opening switch (POS) and a bremsstralung diode. A realistic geometry that closely approximates the Decade Module 1 (DM1) was used in conjunction with a switch opening model to simulate power-flow in an inductive energy store pulsed-power system. Several assumptions were made concerning the emission of ions from the high density POS plasma ($n \sim 10^{15}$ cm^{-3}) and the downstream anode, as well as, the distribution of plasma in the POS-to-load region to assess the role of ion space-charge on the delivery of energy to the diode load. It is found that ion emission from the POS plasma allows a low density plasma ($n \sim 10^{12}$ cm^{-3}) to propagate down the transmission line between the POS and load at about 1 cm/ns. The simulations also show that a large fraction of the current arrives at the load coincidentally with the arrival of this low density plasma. However, the load currents predicted from simulations are too low to explain the measured radiation on DM1. When ion emission is allowed from the anode between the POS and load, additional electron current can propagate along the anode and into the load. When plasma is placed in the POS-to-load region it is found that current transfer is enhanced by the presence of ion space-charge in the POS-to-load region. The enhancement is evident only in regions where the plasma density is highest and goes away as plasma ions are removed.

INTRODUCTION

DECADE is a 16-module x-ray simulator that is currently being designed by Primex Physics International (PI). It is designed with a combination of water-line and inductive-energy-store technologies and uses a plasma-opening switch (POS) as the final power conditioning element.[1] A single DECADE module should deliver about 100 kJ of electrical energy an electron-beam diode with a peak voltage of 1.8 MV and a pulse duration of about 100 ns. If successful DECADE will be the first x-ray simulator in the U.S. based on inductive-energy-store pulsed-power technology.

As part of the design process two modules (DM1 and DM2) have been built and are being used as test beds for the POS and other critical components. Each module produces a 1.8 MA current pulse into the POS with a rise time of approximately 300 ns. Experiments on DM2 have been primarily devoted to an assessment of the magnetically controlled plasma opening switch (MCPOS).[2] In this type of POS the conduction and opening processes are controlled by external magnetic fields. The results from the MCPOS experiments will not be considered here. Experiments on DM1 have been devoted to understanding a POS geometry in which no external magnetic fields are used. In this type of POS, the conduction phase is controlled by J×B forces which act to distort and redistribute the POS plasma[3] and opening is believed to occur by the formation of a vacuum gap[4].

The first series of shots on DM1 produced an average of 11.6 krads(Si). These results sparked an effort to increase the radiation output and assess whether the present design could produce the 20 krad(Si) goal envisioned for DECADE. These results have been since improved to 16 krad(Si) with several shots exceeding the 20 krad(Si) goal.[5] An important part of this effort has been to better understand and characterize the current losses that occur when the POS opens and transfers current to the electron-beam diode load. A schematic of the DM1 front end

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14. ABSTRACT
In this paper we present results from recent particle-in-cell (PIC) simulations regarding power-flow between a plasma opening switch (POS) and a bremsstralung diode. A realistic geome~ that closely approximates the Decade Module 1 (DMl) was used in conjunction with a switch opening model to simulate power-flow in an inductive energy store pulsed-power system. Several assumptions were made concerning the emission of ions from the high density POS plasma (n-1015 cm-3) and the downstream anode, as well as, the distribution of plasma in the POS-to-load region to assess the role of ion spacecharge on the delivery of energy to the diode load. It is found that ion emission from the POS plasma allows a low density plasma (n-1012 cm-3) to propagate down the transmission line between the POS and load at about 1 Crn/ns. The simulations also show that a large fraction of the current arrives at the load coincidentally with the arrival of this low density plasma. However, the load currents predicted from simulations are too low to explain the measured radiation on DM1. When ion emission is allowed from the anode between the POS and load, additional electron current can propagate along the anode and into the load. When plasma is placed in the POS-to-load region it is found that current transfer is enhanced by the presence of ion space

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showing the location of anode and cathode current measurements is shown in Fig. 1. The letter labeling each current probe corresponds to the axial location and the numbers in parentheses indicate the number of azimuthal probes that are averaged to compute the current. In addition to the current measurements, dose was measured using a calibrated PIN diode and thermo-luminescent dosimeters (TLD's).

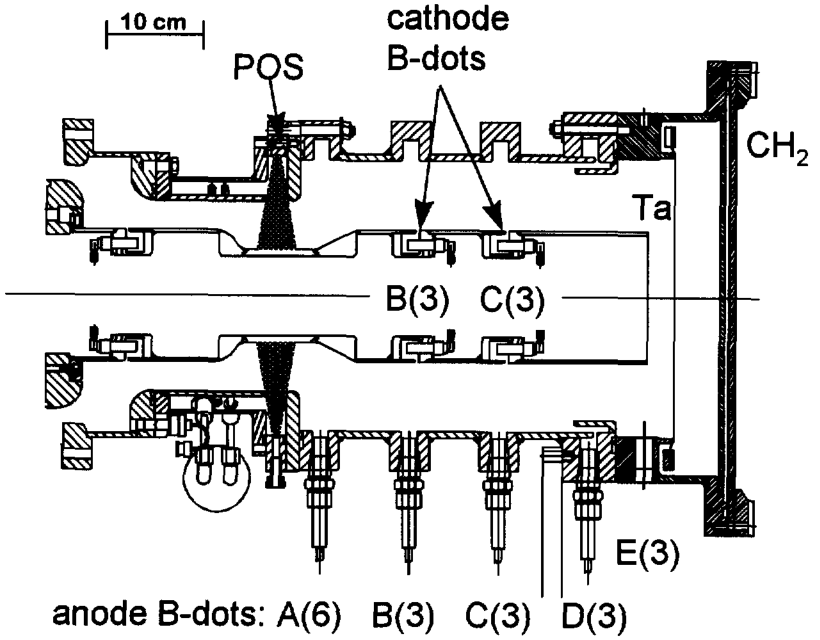


Figure 1: A schematic of the front end of DM1 showing the location of anode and cathode current measurements in the POS-to-load region.

An example of measurements from the current probes for both high impedance loads (Fig. 2a) and low impedance loads (Fig. 2b) are shown in Fig. 2. The difference in the time of arrival of current at the various anode probe locations for both the high and low impedance loads show the propagation of current down the transmission line between the POS and load at a speed of about 1 cm/ns. The peak load currents (anode D) at peak power for both cases is approximately 600-700 kA. Results from an analysis of the radiation measurements are consistent with these current measurements.[6,7] It is important to note that, for the low impedance load, there is very little difference between the anode and cathode current measurements at peak power (t~250 ns). For the high impedance load the anode and cathode probes differ significantly at peak power indicating that a large fraction of the load current is electron flow current. This electron flow may be greatly influenced by plasmas in the POS-to-load region that either originate from the POS plasma and are present at the time of opening or evolve off of the electrode surfaces as the POS opens.

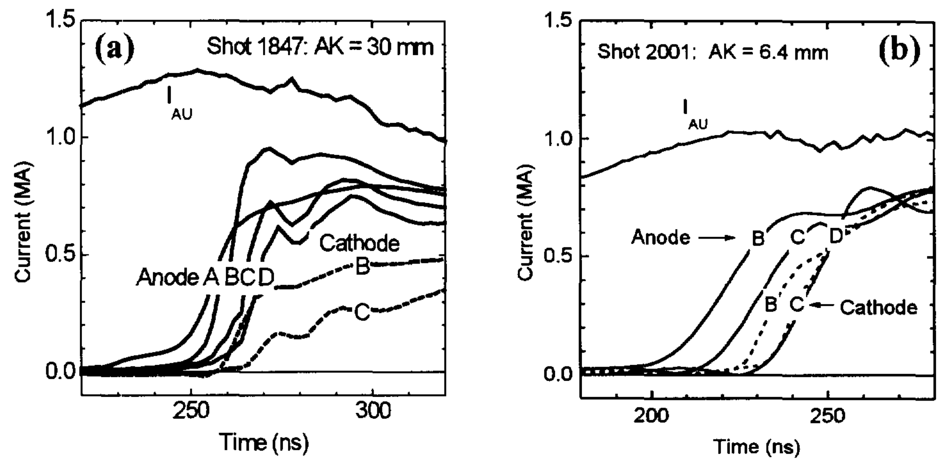


Figure 2: Current measurements from DM1 for (a) a 30 mm diode A-K gap (Z_L=14 Ω) and (b) a 6.4 mm diode A-K gap (Z_L=4 Ω).

SIMULATION MODEL AND RESULTS

This paper presents results from particle-in-cell (PIC) simulations of the power-flow on DM1. A schematic of the opening model for the POS used in the simulations, along with the simulation geometry is shown in Fig. 3. A dynamic gap formation model is used to approximate the final stages of the opening phase of the POS. The high density plasma that connects to the anode is treated as a perfect conductor that can freely emit ions. For the work presented here the charge to mass ratio of the emitted ion species is taken to be Z/A=3/5. This ion charge-to-mass ratio was used so that the plasma that evolves off the high density plasma in the simulations reaches the load when peak power occurs in the experiments. The entire cathode surface was treated as a space-charge-limited electron emitter. The POS gap is initially filled with plasma making it initially very conductive. Current is assumed to flow upstream of the POS at t=0 where magnetic energy is stored. The ions in the initial prefill are given an initial velocity toward the cathode and taken to be so massive that they do not respond to the electromagnetic fields as they clear the POS gap. Previous simulations showed that, as the initial plasma clears the gap, the POS flow impedance increases and the stored magnetic energy flows past the POS and into the region between the POS and load.[8] These simulations also showed that a significant amount of load current was in electron flow that was concentrated along the anode. In contrast to the resistive loads used in Ref. 8, the simulations presented in this paper use a self-consistent diode model based on space-charge-limited emission of electrons and ions. This produces a time varying load impedance that begins as an open circuit and falls as the emission electric field threshold is exceeded and electron and ion flow in the diode is established. The operating impedance of the load is determined by the diode radius (R=6.4 cm) and AK gap.

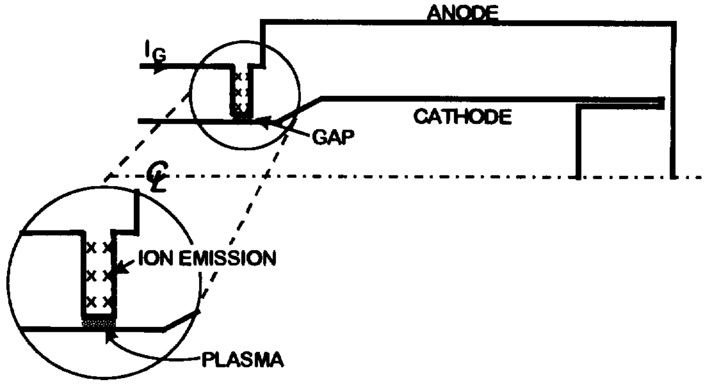


Figure 3: A schematic of the simulation model used to study power-flow between the POS and bremsstrahlung diode on DM1.

Snapshots of the ion positions from a simulation where ion emission is allowed only from the POS plasma and no plasma exists in the POS-to-load region at the time the POS opens are shown in Fig. 4. The diode A-K gap for this simulation was 25 mm and the upstream current at t=0 is taken to be 1.4 MA. Electrons that are emitted in the POS gap become magnetically insulated and flow into the POS-to-load region. The electron flow attracts ions from the POS and form a low density plasma that moves down the transmission line between the POS and load at approximately 1 cm/ns. The density of this plasma is on the order of 10^{12} cm^{-3} and thus many orders of magnitude smaller than the injected POS plasma density ($n_{POS} \sim 10^{15}$ cm^{-3}). Figure 4d shows current probes from the simulation at 5 cm intervals along the anode with the first probe located at z=-0.5 cm (I_G). The current probes show that current propagates down the transmission line between the POS and load with this low density plasma at about 1 cm/ns. When the plasma reaches the load (at t=45 ns) the load current (z=40 cm) rises and peaks at about 200 kA in about 40 ns. This simulation shows many similarities to the measurements except that the load current predicted from simulation is too low to explain the measured radiation.

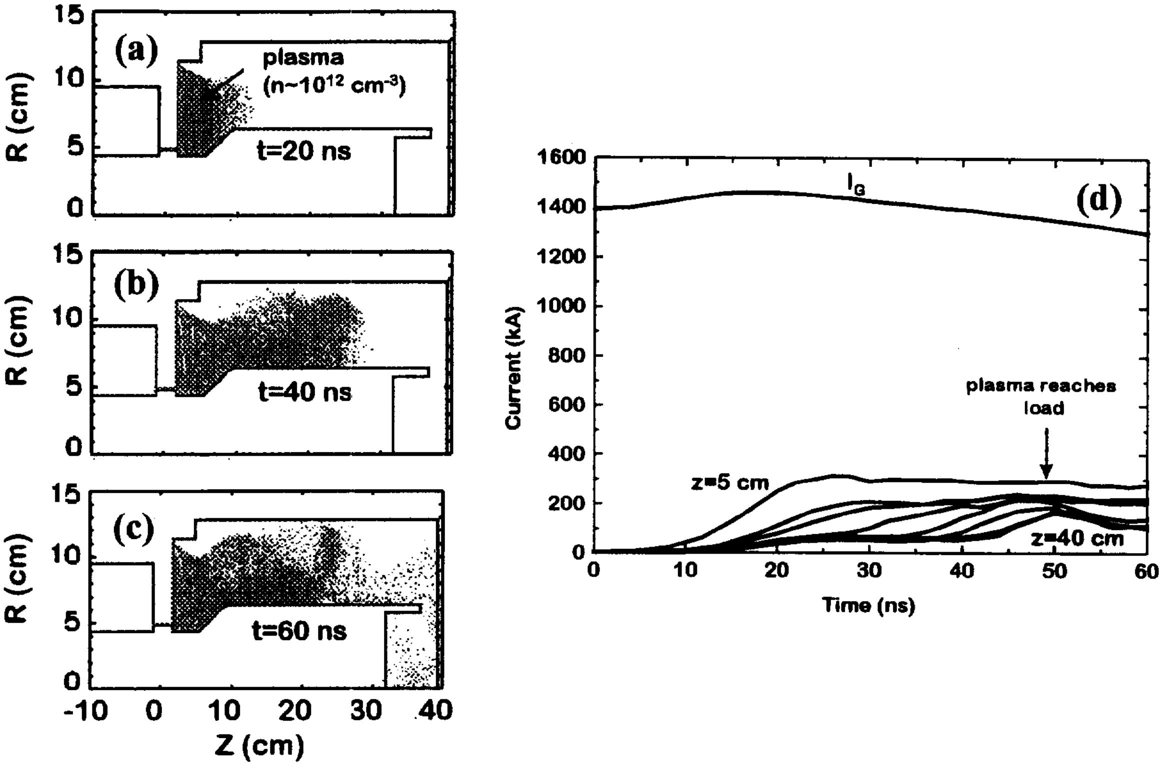


Figure 4: A plot of the ion positions at (a) t=20 ns, (b) t=40 ns, and (c) t=60 ns for the case where ion emission is allowed only from the POS plasma only. (d) The generator current (I_G) and anode current signal in the POS-to-load region at 5 cm intervals with the first probe located at z=5 cm.

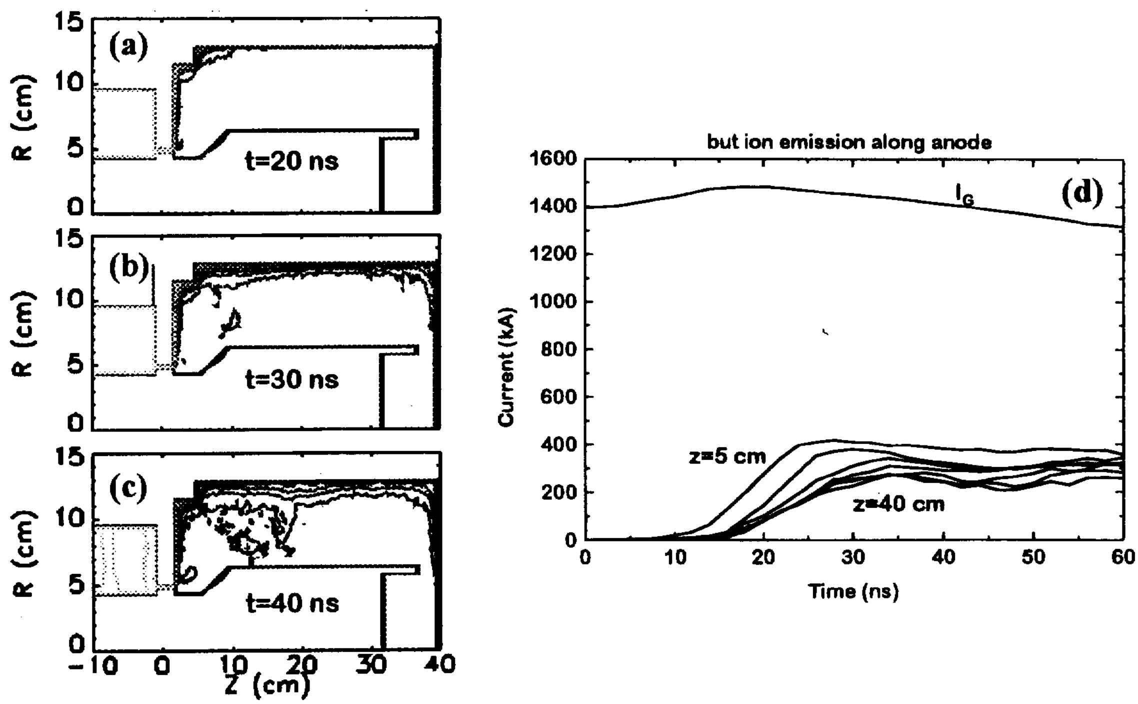


Figure 5: A plot of the current enclosed contours at (a) t=20 ns, (b) t=40 ns, and (c) t=60 ns for the case where ion emission is allowed from the POS plasma and along the anode surface in the POS-to-load region. The contour levels are spaced at 100 kA intervals. (d) The generator current (I_G) and anode current signals in the POS-to-load region at 5 cm intervals with the first probe located at z=5 cm.

To investigate the role of ion production at the anode on the coupling of current between a POS and an electron beam diode, a simulation was run with ion emission enabled from the entire anode surface downstream of the POS. All other parameters were the same as in the simulation shown in Fig. 4. In the DM1 experiments, ions can be emitted from the anode as a result of surface plasma formation caused by electron energy deposition as the POS opens. In the simulations, the emission of ions was not controlled by local energy deposition but instead ion emission was enabled from a particular region of the anode when the local electric field exceeded 100 kV/cm. The current-enclosed contours at several times, along with the anode current signals for this simulation are shown in Fig. 5. The current-enclosed contours show that electron flow propagates toward the load along the anode. The emitted ions partially neutralize the electron space-charge and reduce the local electric field near the anode surface. This allows the magnetic force to bend the electron orbits away from the anode surface. This allows the electrons move axially down the anode and strike the surface at a new location where additional plasma is created and the whole process is repeated. This bootstrap mechanism, which is similar to what occurs in a pinched beam diode[9], allows for more electron current to be transferred to the load. The current probes shown in Fig. 4d show that an additional 100 kA can be transported to the load as a result of ion emission from the anode. However, this is still too low to explain the radiation measurements.

The final two simulations had a plasma prefill in the POS-to-load region. The density profile in R was taken to be uniform and the axial profile is shown in Fig. 6 . The density near the POS was taken to be 5×10^{13} cm^{-3}, decreasing rapidly to 5×10^{11} cm^{-3} near the load. In addition to plasma in the POS-to-load region, the final two simulations differed from the previous two simulations in that the initial current was 1.0 MA and the diode A-K gap was 6 mm. The only difference between the two simulations with plasma in the POS-to-load region was whether or not ion emission was enabled from the anode. In both simulations ion emission was enabled from the POS plasma.

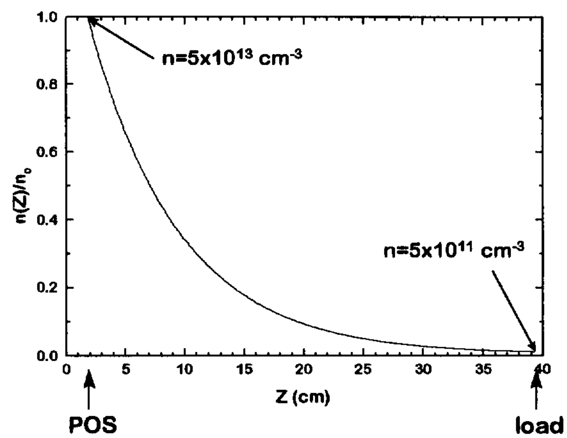


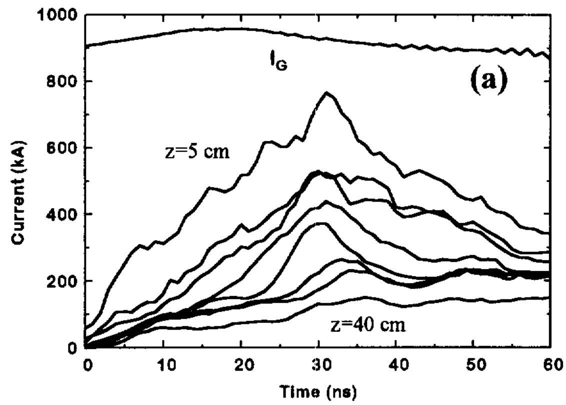
Figure 6: The axial density profile used in the simulations with plasma between the POS and load.

Figure 7a shows the anode current signals for a simulation with plasma in the POS-to-load region but with ion emission from the anode disabled. The results show that much larger currents exist in regions where the plasma density is high. However, this enhancement disappears as ions are removed from the initial plasma prefill. When ion emission from the anode is enabled, Fig. 7b shows that the current enhancement can be prolonged if ions are replaced by emitted ions. However, the load currents are still not large enough to explain the measured radiation.

CONCLUSIONS

In this paper we have explored the role that ion space-charge might play in the coupling of current between a POS and a electron-beam diode load. When ion emission is only allowed from the POS plasma, the simulations show that a low density plasma expands into the POS-to-load region. This plasma carries current with it as it expands toward the load at about 1 cm/ns. When ion emission from the anode is enabled, the simulations show that current transfer is enhanced.

Plasma in the POS-to-load region can result in a more distributed current flow pattern with the best current transfer to regions where the plasma density is highest. The simulation results suggest that, to explain the measured load current, ion space-charge is probably present in the POS-to-load region. The source of these ions are either from the POS itself or are produced by electron-beam bombardment of the anode surface in the POS-to-load region. More detailed information about the distribution of plasma in the POS-to-load region during a shot would help understand the origins of this plasma. It is hoped that, with additional simulations and experiments, the current transfer efficiency to a electron-beam diode load can be better understood and improved.



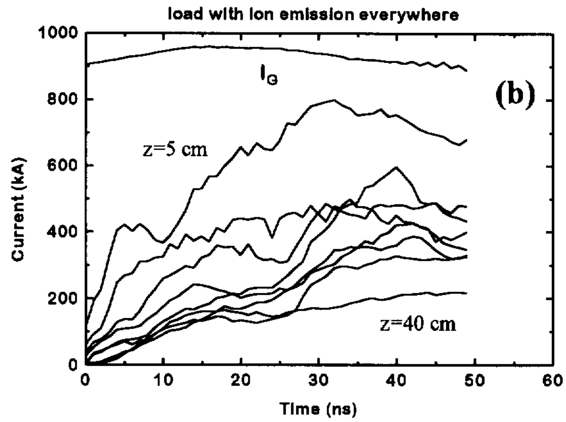


Figure 7: The anode current signals from simulations with a plasma prefill in the POS-to-load region. (a) ion emission from the anode is disabled. (b) ion emission from the anode is enabled. The generator current (I_G) and anode current signals in the POS-to-load region at 5 cm intervals with the first probe located at z=5 cm.

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